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Magma volume, volatile emissions, and stratospheric aerosols from the 1815 eruption of Tambora

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[1] We suggest that the Tambora 1815 eruption was smaller than previously thought, yielding 30–33 km^3 of magma. Valuable insight into the eruption is gained by comparing it to the much smaller 1991 Pinatubo event, which had a similar eruption style and rate. By measuring pre- and post-eruption sulfur concentrations in 1815 ejecta, we estimate that Tambora released 53–58 Tg ($5.3–5.8 \times 10^{13}$ g) of SO_2 within a period of about 24 hours on 10–11 April, 1815. This was sufficient to generate between 93 and 118 Tg of stratospheric sulfate aerosols. A value within this range, distributed globally, agrees well with estimates of aerosol mass from ice-core acidity and the radiative impact of the eruption. In contrast to other recent explosive arc eruptions, the Tambora ejecta retain a record of the sulfur mass released, with no "excess sulfur". *INDEX TERMS:* 8404 Volcanology: Ash deposits; 8409 Volcanology: Atmospheric effects (0370); 8414 Volcanology: Eruption mechanisms; 8439 Volcanology: Physics and chemistry of magma bodies; 8499 Volcanology: General or miscellaneous. **Citation:** Self, S., R. Gertisser, T. Thordarson, M. R. Rampino, and J. A. Wolff (2004), Magma volume, volatile emissions, and stratospheric aerosols from the 1815 eruption of Tambora, *Geophys. Res. Lett.*, *31*, L20608, doi:10.1029/2004GL020925.

1. Introduction

[2] The 1815 eruption of Tambora has long been recognized as the main cause of "the year without a summer" (1816), which occurred concurrently with a great atmospheric aerosol perturbation [*Stothers*, 1984; *Rampino et al.*, 1988]. We show here that valuable information can be learned about the 1815 eruption by comparing it with the much smaller (~5 km^3) 1991 Pinatubo event, which had a similar eruptive sequence and style. Our reassessment of Tambora's eruptive style permits revision of the estimated eruptive size to a bulk volume of 107–113 km^3 (30–33 km^3 of magma), smaller than earlier estimates which range from 175 to >200 km^3. We also recalculate the amount of volatiles released by the eruption using the petrologic method [e.g., *Devine et al.*, 1984], but with newer techniques for analyzing volatile elements (Supplementary data A1[1]). The new estimate of sulfur volatiles released is 53–58 Tg SO_2.

2. Eruption Style: Comparison With Pinatubo 1991

[3] The June 15, 1991 Pinatubo eruption, Philippines, produced ~5.3 km^3 of dacitic magma, equivalent to ~1.3×10^{13} kg of magma, of which 90% was expelled in a period of climactic activity lasting as little as 3.5 hours [*Scott et al.*, 1996]. The average mass-eruption rate was thus 9.1×10^8 kg s^{-1}, which sustained an eruption column in excess of 40 km high (Figure 1) with an umbrella cloud spreading out at an altitude of ~35 km [*Holasek et al.*, 1996]. The 5.3 km^3 volume may be a minimum estimate [*Koyaguchi and Ohno*, 2001] and a longer duration has also been suggested, but the estimated mass flux remains at ~9×10^8 kg s^{-1}. At this rate, 24 hours of activity would produce 7.8×10^{13} kg of magma (~33 km^3 dense rock equivalent (DRE) deposit volume). The high eruption column was sustained during the climactic phase, with synchronous column collapse occurring, except for the first 20–30 minutes. Co-ignimbrite ash and gas clouds lifting off the column-collapse-fed pyroclastic flows were recycled back into the vertical convective system and dispersed by the umbrella cloud (Figure 1), forming a significant portion of the distal ash fallout [*Koyaguchi and Ohno*, 2001; *Dartevelle et al.*, 2002].

[4] The Tambora event has fewer constraints on its eruptive parameters, which are assessed and revised here. After precursory activity, including a short, high-intensity Plinian event on April 5, 1815 [*Sigurdsson and Carey*, 1989], the volcano went into a climactic phase at around 19:00 hrs local time on April 10, and erupted for about a day. A recent review of historic records [*Oppenheimer*, 2003] underlines the fact that few details of the eruption sequence after the first 2–3 hours can be gleaned. At the onset of the climax, another high intensity Plinian column produced a pumice fall deposit recognized in proximal areas [*Self et al.*, 1984; *Sigurdsson and Carey*, 1989, unit F4]. Reports also suggest that column collapse occurred within an hour of the onset, and a duration of ~24 hours of climactic activity appears reasonable [*Self et al.*, 1984; *Stothers*, 1984]. Based on the occurrence of intra-ignimbrite pumice fall layers [*Self et al.*, 1984, Figure 3], we earlier suggested that fall and flow deposition was simultaneous or alternating, indicating synchronous fall and flow deposition throughout much of Tambora's climactic phase. A sustained but partially collapsing eruption column, augmented by co-

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[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL020925.

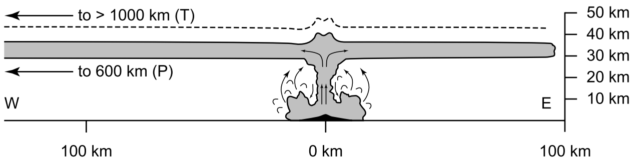

Figure 1. Simple sketch of 1991 Pinatubo umbrella cloud, illustrating augmentation of vent-derived (Plinian) eruption column and umbrella cloud by co-ignimbrite ash columns lifting off pyroclastic flows formed at the same time. Pyroclastic flows from Tambora entered the sea ~20 km from source. Co-ignimbrite ash clouds were recycled back into a sustained but partially collapsing eruption column. Dashed line illustrates height [*Sigurdsson and Carey*, 1989] and possible extent of Tambora umbrella cloud.

ignimbrite ash clouds that were recycled back into the main eruption column (Figure 1), fed an umbrella cloud that produced the extensive 1815 ash fall deposit.

[5] Pinatubo's ash dispersal and thickness at various distances indicate that at the observed edge of the 4-hour-old umbrella cloud, ~580 km downwind, ~1 cm of ash fell [*Wiesner et al.*, 2004] and the umbrella cloud had an area of ~315,000 km^2. At 1000 km downwind, the ash fall was <0.1 cm thick. From the isopach areas of the Tambora ash deposit based on our map in *Self et al.* [1984, Figure 5], and taking the 1 cm isopach as indicative of the edge of the umbrella cloud, as for the Pinatubo fallout, we estimate that the Tambora cloud had an area of >980,000 km^2, three times that of Pinatubo's (Supplementary data A2). In comparison, the 1815 ash fall was 10–20 cm thick at 500 km downwind, and 1–2 cm thick at 1000 km from vent.

3. Re-estimated Volume of 1815 Deposits and Mass Eruption Rate

[6] By far the most voluminous deposit of the 1815 eruption was the widespread and thick ash fall, unit F5 of *Sigurdsson and Carey* [1989], which we propose was formed by fallout from an umbrella cloud, as at Pinatubo. We suggest that F4 and F5 form the same ash layer far from the volcano, and that pyroclastic flow and fall deposition occurred synchronously, thus removing the need to invoke a large volume of ignimbrite as the origin of the widespread F4/F5 ash fall. We also suggest that pyroclastic flow deposits around the volcano were of subordinate volume. Calculation of the ash-fall bulk volume from data in A2 (Figure 2) yields 99.7 km^3; the proportion outside the 1 cm isopach is 4.4% of this amount and is included. The thickness data used to compile the ash dispersal map are, for the most part, of freshly fallen ash, thus a conversion to a DRE volume is made using an average deposit density of 660 kg m^{-3} [*Self et al.*, 1984; *Stothers*, 1984] and a magma density of 2470 kg m^{-3}. This yields 26.6 km^3 (Table 1), to which must be added a volume of ignimbrite and the F1–F3 ash-fall deposit DRE volume, which is ~0.6 km^3 (Table 1). *Stothers* [2004] reports a density estimate of distal, freshly fallen ash from near the edge of the dispersal area interpreted from contemporary reports. If this value is used to convert from bulk to magma density, the DRE volume of the widespread ash fall deposit is reduced to 25.6 km^3.

[7] It is difficult to estimate an accurate volume for the ignimbrite as much was deposited in the sea around Tambora. Secondary explosions added fine ash to the atmosphere [*Sigurdsson and Carey*, 1989], which later fell with the F5 layer. However, considering the lack of reports of new land being added to the Sanggar Peninsula around Tambora, a comparatively small, on-land, lithic-free bulk volume 5.7 km^3 of ignimbrite is adopted from previous estimates [*Sigurdsson and Carey*, 1989]. Thus an ignimbrite DRE volume of 2.8 km^3 brings the erupted total to ~30 km^3. If we consider that a similar volume of ignimbrite was deposited offshore, the total volume increases to ~33 km^3. This range (30–33 km^3) is approximately 1/3 smaller than previous estimates.

[8] The mass of the 30-km^3 Tambora deposit is estimated to be 7.4×10^{13} kg (8.1×10^{13} kg for a 33 km^3 volume). From this, the eruption-rate estimate for a 24-hr duration of the climax is 8.6×10^8 kg s^{-1} (9.4×10^8 kg s^{-1} for 33 km^3 volume), similar to that calculated for Pinatubo, suggesting that both events proceeded at similar intensities. The primary reason that Tambora's umbrella cloud was more widespread, and the ash fall considerably thicker, was due to the longer time required to evacuate a significantly larger magma body.

4. Tambora 1815 Magma and Estimates of Pre-eruptive Sulfur (Volatile) Concentration

[9] Tambora erupted a homogeneous batch of silica-undersaturated, nepheline-normative trachyandesitic magma [*Self et al.*, 1984; *Foden*, 1986], quite different from typical calc-alkaline arc magmas such as Pinatubo. The studied Tambora pumice clasts have a glassy matrix with an average of ~10 wt% phenocrysts (expressed vesicle-free, estimated from modal abundances converted to mass using appropriate crystal densities), comprised predominantly of plagioclase and minor clinopyroxene, Ti-magnetite, biotite, olivine and apatite. Unlike other phenocrysts that are characterized by uniform compositions, plagioclase in the 1815 magma spans a wide compositional range and occurs as two distinctive populations: (1) unzoned, of nearly constant composition ($An_{58\pm6}$) and (2) zoned, with calcic cores ($\leq An_{91}$) and variably thick rims of $An_{58\pm6}$, identical

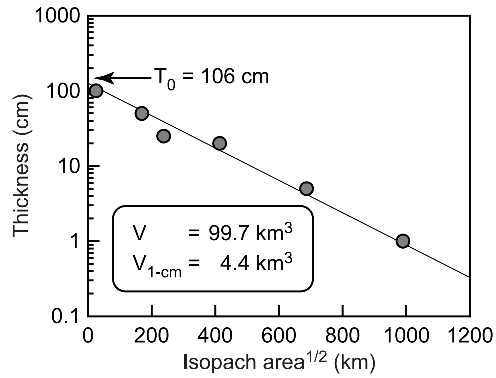

Figure 2. Log of thickness vs. square root of area for distal ash fall from 1815 Tambora eruption based on our isopach map [*Self et al.*, 1984, Figure 5]. T_0 is extrapolated maximum thickness; V is bulk ash fall volume; $V_{1\text{-cm}}$ is volume beyond 1-cm isopach.

Table 1. Tambora 1815 Eruption Volumes

Deposit	Bulk Volume (km^3)	Density ($kg\ m^{-3}$)	Volume (DRE) (km^3)[a]	Mass (kg)
F4/F5 ash fall deposit[b]	99.7	660	26.6	6.6×10^{13}
Pre-F4 ash fall deposits[c]	1.6	900	0.6	1.4×10^{12}
Ignimbrite on land	5.7[c]	1220	2.8[d]	6.9×10^{12}
Ignimbrite in sea	≤5.7	1220	≤2.8	$\leq 6.9 \times 10^{12}$

[a]Assuming a melt density of 2470 $kg\ m^{-3}$.
[b]Based on dispersal of distal ash fall [*Self et al.*, 1984].
[c]After *Sigurdsson and Carey* [1989].
[d]DRE volume for ignimbrite on land made using mean of five density measurements (1220 $kg\ m^{-3}$).

to the unzoned population. Comparison of plagioclase rim and matrix glass compositions to experimental data [*Housh and Luhr*, 1991] and QUILF geothermometry [*Andersen et al.*, 1993], assuming equilibrium between ferromagnesian silicate phases and Ti-magnetite, indicate that the magma equilibrated at a pressure of ~100 MPa, T = 930–980°C, and fO_2 ~2 log units above the fayalite-magnetite–quartz buffer, a slightly lower value than highly oxidized arc magmas such as 1991 Pinatubo dacite [*Evans and Scaillet*, 1997].

[10] Glass inclusions in the 1815 Tambora magma are commonly found in plagioclase, which crystallized throughout the evolution of the magma body. Only inclusions trapped near plagioclase phenocryst rims and those in cores of unzoned plagioclase phenocrysts were considered in this study, as they are similar in composition to matrix glass and are interpreted as being most representative of the pre-eruptive melt composition [*Devine et al.*, 1984; *Sigurdsson and Carey*, 1989].

[11] Glass inclusions in plagioclase rims and compositionally similar cores consistently contain 689 ± 80 ppm S, 1720 ± 169 Cl, and 847 ± 307 ppm F, which are considered to represent the pre-eruptive volatile content of the 1815 magma (Table 2). In contrast, the matrix glass, which is representative of the degassed magma, contains an average of 290 ± 74 ppm S, 1511 ± 132 ppm Cl, and 601 ± 301 ppm F (Table 2). Plagioclase-hosted glass inclusions have an average of ~400 ppm more S than the matrix glass, suggesting that this amount was released from the magma during explosive eruption. In contrast to other trachyandesitic-phonolitic magmas such as Vesuvius AD 79 (1400 ppm [*Cioni*, 2000]) and Laacher See 12,900 BP (1490 ppm [*Harms and Schmincke*, 2000]), sulfur concentration in the 1815 magma was modest.

[12] The amount of S released from the Tambora magma batch upon eruption is estimated by

$$E_{SO2} = 2\ M_V(1 - W_{xls})(C_{incl} - C_{matrix})/100$$

where E_{SO2} is the SO_2 emission in kg, M_V is the mass of erupted magma in kg (7.4×10^{13}–8.1×10^{13} kg, Table 1), W_{xls} is the mass fraction of crystals in the magma (W_{xls} = 0.10, see above) and $C_{incl} - C_{matrix}$ is the difference between the average S concentrations of the glass inclusions and the matrix in wt% (0.0399 wt%, Table 2). The factor 2 accounts for the difference between the molecular weights of SO_2 and S.

[13] The above calculation yields a release of 53–58 Tg of SO_2 (27–29 Tg S). We believe that this is more precise than previous estimates for the Tambora S release, which range from 17 Tg [*Devine et al.*, 1984] to 43–48 Tg [*Sigurdsson and Carey*, 1992; *Mandeville et al.*, 1993]. This amount is sufficient to yield 108–118 Tg of sulfuric aerosols of a composition 75 wt% H_2SO_4–25 wt% H_2O at 100% conversion of SO_2 to H_2SO_4. From the Pinatubo SO_2 release of 17 ± 2 Tg, it is estimated that ~30 Tg of H_2SO_4 aerosols were generated [*McCormick et al.*, 1995], a conversion efficiency of ~86%. Adopting this gas-particle conversion efficiency, we calculate that 93–102 Tg of H_2SO_4 aerosols were generated in 1815. By comparison, Pinatubo yielded a larger SO_2 release per unit of magma, but, with only 5–6 km^3 erupted, much of this came from a separately sequestered, S-rich volatile phase [*Wallace and Gerlach*, 1994].

5. Discussion

[14] The new estimate of 93–118 Tg of sulfate aerosols generated from 53–58 Tg of SO_2 is smaller than previous estimates of the mass of Tambora's aerosols, which range from 150 Tg from ice core acidity peak size [*Hammer et al.*, 1980] to 200 Tg [*Stothers*, 1984; *Sigurdsson and Carey*, 1989]. It is in agreement with *Zielinski*'s [1995] estimate of a maximum of 107 Tg from acidity in the GISP2 ice core. Tambora's aerosol cloud was global in extent, as testified by ice-core acidity peaks in both hemispheres [*Langway et al.*, 1995], and is one of the major inter-hemispheric ice-core signals of the past 5 centuries. Aerosols and acid fallout were not evenly distributed over both hemispheres. Moreover, recent studies of radiative forcing from an energy balance model, based on ice core acidity data and temperature time series [*Crowley and Kim*, 1999; *Hyde and Crowley*, 2000] suggest, for a scaled time series of eruptions, that the averaged global Tambora effect was −6.1 W m^{-2}, and that up to 2/3 of the Tambora aerosol mass was in the Southern Hemisphere. This is in good agreement with composite temperature records of the past few 100 years [e.g., *Mann et al.*, 1998], which indicate a cooling of 1.0–1.5°C after the Tambora eruption. The forcing required to cause this change in radiation is about 3 times the mass of the Pinatubo aerosols [*Shindell et al.*, 2003], consistent with a Tambora aerosol loading in the same range as independently calculated here.

Table 2. Major Element (wt%) and Volatile (S, Cl, F; ppm) Contents (With 1σ Standard Deviation) of Melt Inclusions in Plagioclase Rims (and Compositionally Similar Plagioclase Cores) and Matrix Glasses From 1815 Tambora Pumices

	Melt Inclusions (n = 30/26)[a]		Matrix Glass (n = 126/78)	
SiO_2	56.17	(0.64)	58.30	(0.49)
TiO_2	0.66	(0.09)	0.53	(0.03)
Al_2O_3	18.90	(0.36)	19.32	(0.26)
FeO	4.82	(0.33)	4.54	(0.25)
MnO	0.18	(0.03)	0.18	(0.02)
MgO	1.52	(0.17)	1.37	(0.11)
CaO	3.27	(0.25)	3.24	(0.33)
Na_2O	5.39	(0.40)	5.43	(0.27)
K_2O	6.06	(0.26)	6.25	(0.31)
P_2O_5	0.49	(0.12)	0.35	(0.04)
Total	97.46	(0.39)	99.51	(0.59)
S	689	(80)	290	(74)
Cl	1720	(169)	1511	(132)
F	847	(307)	601	(301)

[a]Number of major element analyses/volatile analyses.

[15] *Stothers*' [1984] estimate of 200 Tg for the Tambora aerosol cloud based on observations made over Europe may also be an overestimate, possibly due to a local dense region of stratospheric aerosols. A much lower average mass loading in the Northern Hemisphere is suggested by the studies above [e.g., *Hyde and Crowley*, 2000]. Based on the similarity in global coverage and the rate of decay of the Pinatubo aerosol cloud, the Tambora aerosols would have persisted, and declined in concentration, over three years after April 1815.

6. Conclusions

[16] The climactic 1815 Tambora eruption had a similar intensity and style as the 1991 eruption of Pinatubo, but lasted approximately six times longer in order to evacuate a much larger magma chamber. This study provides new estimates for the mass of magma and aerosol generated by Tambora in 1815: 7.4–8.1 $\times$ 10^{13} kg (30–33 km^3) of magma, 53–58 Tg SO_2, and between 93 and 118 Tg of sulfate aerosols. The aerosol cloud was distributed globally, as suggested by ice-core acidity studies, but with more aerosol in the Southern than in the Northern Hemisphere. An aerosol mass in this range is consistent with independent reconstructions of radiative and temperature changes after 1815, which suggest a reduction in radiative forcing of $\sim$6 W m^{-2} and a global cooling of 1–1.5°C.

[17] The S content of the 1815 magma was relatively modest, and the large mass of S released reflects the large mass of magma erupted. The estimated S mass from Tambora does not require that a significant portion of the released gas was sequestered separately from the melt, as with other recently-erupted arc magmas [*Scaillet et al.*, 2004]. The calculated magma volume and aerosol mass still place Tambora as one of the largest eruptions of the past millennium [*Self et al.*, 1984]. Other historic eruptions were probably of similar magnitude to the 1815 eruption, e.g., Kuwae, *c.*AD 1453 [*Monzier et al.*, 1994] and an unknown event *c.*AD 1259 [*Zielinski*, 1995]. Tambora released less SO_2 than the Laki eruption of 1783-4, $\sim$120 Tg [*Thordarson and Self*, 2003], but generated a larger amount of stratospheric aerosols due to its greater eruption column height.

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